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Fuel properties, engine performance and emission characteristic of common biodiesels as a renewable and sustainable source of fuel

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ABSTRACT

The energy security concern has been established as an alarming issue in context of petro diplomacy now-a-days. Global warming with rapid changes in climate, increase in price and depletion in reserve of fossil fuel are leading scientists to work toward alternative fuel. Biodiesel could be an answer for the alternative fuel, which is renewable, biodegradable, non-toxic and less polluting. This paper is comprised of fuel properties, engine performance and emission characteristics of commonly used different vegetable (jatropha, palm, coconut, cottonseed, sunflower, soybean and canola/rapeseed) based biodiesel derived from experimental results at different conditions performed worldwide. It can introduce a potential guideline to improve engine performance and emission characteristics using different biodiesels and their blends as well. This paper provides a comparative baseline to make an easy comparison among the biodiesels in respect of fuel properties, engine performance and emission characteristics.

Contents

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1. Introduction

The world is moving towards an energy crisis because of the depleting reserve of fossil fuels. In addition, the rapid rise in the use of fossil fuel is favoring this depletion. Besides, increasing fossil fuel price, emission of greenhouse gases and the security and diversity of energy are tending the scientists to turn their attention to find out alternative sources of fuel. Biodiesel is one of the best sources of alternative fuel [1]. It is renewable and clean fuel for diesel engines [2,3]. It is also called environment friendly as it is nontoxic, biodegradable, safer to breathe and emits less greenhouse gases [3].

Biodiesel, as an alternative fuel for internal combustion engines, is defined as a mixture of mono-alkyl esters of long chain fatty acids (FAME) derived from a renewable lipid feedstock, such as vegetable oil or animal fat. Biodiesel typically comprises alkyl fatty acid (chain length C14–C22) esters of short-chain alcohols, primarily, methanol or ethanol [3,4]. Biodiesel is the best candidate for diesel fuels in diesel engines. Production of biodiesel is not a modern invention. The first diesel engine developed by Rudolf Diesel in 1900, was run with groundnut oil [5]. In 1912, Rudolf Diesel also stated that in future the vegetable oils would be an important fuel like petroleum [6]. The awareness about environment is making Rudolf Diesel's prediction true today [5].

Vegetable oils are being used as alternative fuel for more than 100 years after the invention of diesel engine [7]. Depending upon environmental condition, the sources of biodiesel vary from country to country like soybean for North America, sunflower and rapeseed for Europe, palm for Southeast Asia, coconut for tropic and sub-tropic area etc. [8]. However, crude vegetable oils are inferior as fuel in terms of viscosity, heating value, freezing point, etc. Different chemical treatment like transesterification can improve the fuel properties [9,10]. The transesterified vegetable oils are widely being used at present.

Diesel engine has got popularity for its higher thermal efficiency as well as high power to weight ratio. Therefore, it is being widely used in automobiles, power generation and industrial sectors. The diesel power vehicles have about one-third share of total vehicle sold in Europe and USA [11]. However, more stringent emission regulations imposed by the authorities limit its use. Thus, cleaner emission property of biodiesel gives hope for its wide use in diesel engine. It can be used directly in the existing diesel engines without any modification [12,13]. A lot of research efforts have been given on production of biodiesel as well as engine performance and emission characterization [14–23]. Most of them found relatively poor fuel property of vegetable oils and their biodiesels. The brake power and the brake torque of the engine using crude vegetable oil and their biodiesel were relatively lower than that of ordinary petroleum diesel [24–37]. But in some cases the brake thermal efficiency was higher [24,33,38–60]. Again biodiesel blends sometimes gave better brake power and torque than ordinary diesel. On the other hand, biodiesel and its blends improve emission characteristics with exception in case of NO_x [52,61–66]. However, many researchers also found relatively lower NO_x emission using biodiesel and their blends [67–74].

In this study, peer reviewed articles of highly rated journals of seven commonly used biodiesels (jatropha, palm, coconut, cottonseed, sunflower, soybean and canola/rapeseed) have been reviewed. This report focuses on comparison fuel properties, engine performance and emission characteristics of seven biodiesels in a single platform. Each of them is discussed elaborately in different sections. Finally different research results are presented in tabular form in order to have an easy comparison among them.

2. Fuel properties

Density, viscosity, heating value, flash point, acid value, pour point, cetane number, etc. are considered as the most important properties of a fuel for its application in engine. These properties indicate the quality of the fuel. Engine performance and emission are also directly related to these. There are different types of standard like ASTM, EN, ISO, etc. to define the limit of each of the fuel properties. Among them ASTM is the most widely followed standard. To meet the standard engine performance and emission, the value of the fuel properties must be in the range. In this regard study of fuel properties are the most important part to use any liquid as fuel. Now-a-days, blending is widely being used to improve biodiesel fuel properties. Sometimes biodiesel from two or more feedstock are blended to improve the properties. Use of more feedstocks can easily improve fuel properties rather than two because most of the important fuel properties like density, kinematic viscosity, oxidation stability, flash point, calorific value and cetane number vary linearly in case of multiple fuel blends [75–79]. The most widely used vegetable based biodiesel fuel properties are discussed. Table 1 contains fuel properties of seven discussed vegetable based biodiesels.

2.1. Kinetic viscosity

Fuel flow, spray and atomization characteristics are directly governed by the kinetic viscosity of the fuel. Higher viscosity increases fuel pump power consumption and causes poor spray and atomization [76,110,111] and also increases fuel consumption [41]. In these respects, lower viscosity is desired.

From Table 1 most of the biodiesels have higher viscosity than OD (ordinary diesel). But viscosity of palm and coconut based biodiesel are comparable to OD. Therefore, palm and coconut biodiesel can give improved atomization and lead to better combustion than others.

Table 1
Fuel properties of ordinary diesel and common vegetable based biodiesel [3,33,38–41,43–47,49,51,53–60,77,80–109].

Properties	Kinetic viscosity 40 °C (cSt)	Density (kg/m^3)	Cetane number	Calorific value (MJ/kg)	Flash point (°C)
ASTM limit	1.9–6	–	47 minimum	–	130 °C minimum
Diesel	2.5–5.7	816–840	45–55	42–45.9	50–98
Jatropha	3.7–5.8	864–880	46–55	38.5–42	163–238
Palm	2.95–4.92	843–890	49–65	38.73–40.39	135–259
Coconut	2.61–4.1	844–930	51–60	35–38.1	112–241.5
Cottonseed	4–4.9	874–885	51.2–55	40.32–42.73	70–110
Sunflower	4.5–5.9	877–882	49–52	39.7–40.56	85–178
Soybean	4.08–4.97	884–896	40–53	38.31–39.76	69–144
Canola or rapeseed	4.2–4.5	837–886	49–52.9	36.55–40.5	94–183

2.2. Density

Density and viscosity are directly proportional to each other. Higher density increases energy concentration of fuel [112] and minimizes fuel leakage. It also influences the fuel atomization efficiency [76]. But higher density causes higher viscosity which in return gives poor combustion and effects engine performance and emission.

From Table 1, density of biodiesel is usually higher than OD. But sometimes palm, coconut and canola or rapeseed biodiesel have a density close to OD which can make them superior to others.

2.3. Cetane number

Cetane number (CN) is a prime indicator of the quality of fuel used in compression ignition (CI) engines. It is a dimensionless descriptor. It is related to ignition delay time, i.e., the time elapsed between injection of the fuel and onset of ignition. A shorter ignition delay corresponds to a higher CN and vice versa. Higher CN is desired for CI engine fuel.

Though most of the biodiesels have higher CN than that of OD (Table 1), among them, palm and coconut biodiesel usually have higher CN than other biodiesels. In this respect, these two biodiesels are better than others.

2.4. Calorific value

The calorific value of a fuel is defined as the amount of heat released during combustion when a unit quantity of the fuel is burnt. Higher calorific value for fuel is desired because it facilitates the heat release during combustion and improves engine performance [39,92,113,114].

Table 2
Different experimental engine performance results using jatropha biodiesel compared to OD.

Engine	Test condition	Result			Reference
		Power/torque	Efficiency	BSFC	
3-Cylinder, WC, CI engine, D: 3.44 l, CR:18:1, RS: 2200 rpm	Full throttle at different engine speeds	Increased for 20% to 50% blend, for 100% blend increment of power observed for 2000 rpm and higher speed	–	Higher than OD and increased with the blend ratio but decreased as the engine speed increased	[88]
1-Cylinder, 4S, WC, DI, CR: 1:17, D: 815 cm^3, RP: 8.82 kW, RS: 2000 rpm	Constant speed (1500 rpm and 2000 rpm) at different power	–	Increased by 0.2%–3.5% for 1500 rpm, increased by 0.1%–6.7% for 2000 rpm	For 1500 rpm, the average increment 9.3%; for 2000 rpm, the average increment 6.8%	[40]
1-Cylinder, 4S, WC, CR: 1:17.5 D: 661.45 cm^3 RP: 5.2 kW RS: 1500 rpm	Speed: 1500 rpm IA: 23° bTDC IP: 160 kg/cm^2, different brake powers, different blends (20%, 40%, 60% and 100%)	–	Efficiency decreased as blend ratio increased	–	[84]
	Speed: 1500 rpm IP: 160 kg/cm^2. Different brake powers. Different IT (21°–25° bTDC) for 20% blend	–	IT 23o bTDC gives highest efficiency and higher than OD at high load	–	
1-Cylinder, 4S, WC, RP: 8bhp RS: 1500 rpm	Different brake power for different blends (25%, 50%, 75% and 100%) at constant speed	–	25% blend give comparable efficiency and 100% blend gives maximum 7% decrease of efficiency	Increases with increase of blend ratio	[46]
1-Cylinder, AC, DI, CR: 1:18, D: 395 cm^3 RP: 5.59 kW, RS:3600 rpm	Different speeds (3200 rpm, 2500 rpm, 1800 rpm), different torques (5 Nm, 10 Nm and 15 Nm) and different injection timings (340, 345, 350)	–	Lower than OD	Higher than OD	[116]
1-Cylinder, AC, CR: 1:17.5, D: 947.87 cm^3 RP: 7.4 kW, RS: 1500 rpm	At different loads (0%, 20%, 40%, 60%, 80% and 100%) and different blends (5%, 10%, 20%, 30% and 100%)	–	Lower than OD and decreased with increase of blend ratio	Higher than OD and increase with blend ratio	[117]
1-Cylinder, 4S, DI, WC CR: 1:18.5, D: 1.007 L RP: 19 PS, RS: 2400 rpm	At different speeds (1000–2400 rpm) and different blends (10%, 20%, 50% and 100%)	Torque decreased from 2.65 to 4.75% with the increase of blend ratio	Lower than OD and up to 50% blend, it increased and then remain almost constant	Higher than OD and up to 50% blend, it decreased and then remain almost constant	[118]
4-Cylinder, 4S, TC, CR: 1:18.5, D: 2609 cm^3 RP: 84.5 kW, RS: 3800 rpm	Full throttle at different speeds and also optimized injection parameters to compensate power deterioration	Normally decreased but optimized injection increased than OD	Almost same as OD	Always higher than OD	[119]
1-Cylinder, DI, CR: 1:16.5 RP: 5 HP, RS: 1500 rpm	At different loads (25%, 50%, 75% and 100%) and different blends (20%, 40%, 50%, 60%, 800% and 100%)	–	Up to 80% blend, efficiency was higher than OD, 20% blend gave maximum 36.9% efficiency	Lower than OD for 20% blend, 100% blend gave higher OD, almost same as OD for the other blends	[120]
1-Cylinder, 4S, WC, NA, DI, CR: 1:17.5, D: 661 cm^3 RP: 7 HP, RS: 1500 rpm	Full load, different blends (5%, 10%, 15%, 20%, 25% and 100%), different injection pressure (180, 200, 220 and 240 bar), different IT (22, 27 and 32 deg)	–	Maximum at 220 bar, minimum at 240 bar, maximum at 32 deg, minimum at 22 deg	–	[121]

4S=four stroke, WC=water cooled, AC=air cooled, NA=naturally aspirated, DI=direct injection, CR=compression ratio, D=displacement volume, RP=rated power, RS=rated speed, TC=turbo charged, IT=injection timing, deg=degree.

Usually biodiesels have lower calorific value than that of OD. But cottonseed biodiesel has got the calorific value very close to OD and higher than other biodiesels. Jatropha, palm and soybean biodiesel also have comparable calorific value. So, these biodiesel can give better engine performance than other biodiesels.

2.5. Flash point

Flash point is one of the most important properties of fuel. It indicates the minimum ignition temperature of the fuel. Higher flash point makes fuel safer for handling and storage and prevent unexpected ignition of fuel during combustion.

Table 3
Different experimental engine performance results using palm biodiesel compared to OD.

Engine	Test condition	Result			Reference
		Power/torque	Efficiency	BSFC	
6-Cylinder, 4S, WC, NA, DI, CR: 1:15.9, D: 991 cm^3 RP: 81 kW, RS: 2600 rpm	Full load and constant speed (1500 rpm)	Decreased by 2.5%	Decreased by 0.48%	Increased by 7.5%	[33]
4-Cylinder, 4S, WC, NA, IDI, CR: 1:21.47, D: 449.77 cm^3 RP: 38.8 kW, RS: 4250 rpm	Full load at different speeds and different blends (5%, 20%, 50% and 100%)	Decreased as the biodiesel percentage increased	–	Increased as the biodiesel percentage increased	[124]
1-Cylinder, 4S, AC, NA, DI, CR: 1:18, D: 634 cm^3 RP: 5.4 kW, RS: 1800 rpm	Constant speed (1800 rpm) with different loadings	–	Average about 1% lower for 50% blend and 2% lower for 100% blend	Pure PME has about 10% increment and 50% blend of 20–35% increased with increase of blend ratio	[44]
4-Cylinder, 4S, NA, IDI, WC CR: 21.47:1 RP: 38.8 kW, RS: 4250 rpm	Different engine speed at full load and different blends (10%, 30%, 40%, 60%, 80% and 100%)	10% blend gave almost same as OD and maximum about 7% decreased with increase of blend ratio	Maximum about 8% decreased with increase of blend ratio	Maximum about 11% increased with increase of blend ratio	[89]
6-Cylinder, 4S, DI, WC, NA CR: 15.9:1 RP: 81 kW, RP: 2600 rpm	Full load at different speeds	4–5% reduced	–	9–10% increased	[45]
1-Cylinder, 4S, WC, DI, NA CR: 16.5:1 RP: 3.5 kW, RS: 1500 rpm	Constant speed and different percentages of EGR (0% and 15%)	–	OD at 15% EGR and biodiesel at 0% EGR gave almost the same	OD at 15% EGR and biodiesel at 0% EGR gave almost the same	[125]
1-Cylinder, 4S,DI, NA, AC RP: 4.6 kW, RS: 3500 rpm CR: 22:1, D: 347 cm^3	Different loads, speeds and blends (50% and 100%)	–	–	Higher than OD and increased with increase of blend ratio	[126]
1-Cylinder, 4S, DI, NA,WC CR: 17.5:1 RP:5.2 kW, RS: 1500 rpm D: 662 cm^3	Constant speed (1500 rpm), different load and different blends (25%, 50%, 75% and 100%)	–	Lower than OD and decreased with increase of blend ratio	Higher than OD and increased with increase of biodiesel concentration	[127]
1-Cylinder, 4S, WC, DI, NA D:1.007 L, CR:16.3:1 RP: 11.77 kW RS: 2200 RPM	Constant speed (2000 rpm) and different loads (0%, 25, 50, 75 and 100%)	–	Almost same as OD	Average about 16% increased	[42,43,122,123]

IDI = indirect injection.

Table 4
Different experimental engine performance results using coconut biodiesel compared to OD.

Engine	Test condition	Result			Reference
		Power/torque	Efficiency	BSFC	
1-Cylinder, 4S, FAC, DI, CR: 1:19.9, D: 211 cm^3	Full load, constant speed (3000 rpm) and different fuel blends	Lower than OD and decrease with increase of blend ratio	Lower than OD and decrease with increase of blend ratio	–	[130]
1-Cylinder, 4S, WC, DI, CR: 1:17.5 D: 661 cm^3 RP: 5.2 kW RS: 1500 rpm	Different loads (15%, 30%, 45%, 60%, 75%, 90% and 100%) and different blends (20%, 40%, 60%, 80% and 100%)	–	Same for full load and higher than OD for part load	Higher than OD and increased with increase of blend ratio	[131]
1-Cylinder, 4S, WC, DI, CR: 1:16.3, D: 1007 cm^3 RP: 11.77 kW RS: 2200 rpm	Fixed speed (2000 rpm), different loads (0%, 25%, 50%, 75% and 100%)	–	Almost same as OD	Higher than OD	[42,43]
1-Cylinder, 4S, AC, DI, NA, CR: 1:18.8, D: 367 cm^3 RP: 2.8 kW, RS: 3600 rpm	Full throttle at different speeds (1200–3600 rpm)	About 5% less power	Almost same	Increased by 2–7%	[129]
4-Cylinder, DI, CR: 1:19.5, D: 1.7 L RP: 66 kW RS: 4200 rpm	Different speeds (1500, 2000 and 2300 rpm), different BMEP (1, 2.6, 2, 4.2 bar) and different percentages of EGR (11–32%)	–	Slightly increased for 5% blend and slightly decreased for 20% blend	Almost same for 5% blend and about 4% increased for 20% blend	[128]

FAC = forced air cooled.

Most of the biodiesel have got higher flash point than that of OD. ASTM standard recommends minimum flash point of a biofuel to be 130 °C. Therefore, it is obvious that jatropha and palm biodiesels are better than others in this regard.

3. Engine performance

To use biodiesel as a fuel, the first consideration is its economic aspect. If the crude oil is not widely available, it cannot be used as engine fuel. Engine performance is the next parameter which indicates whether a fuel is economical or not. Brake power, brake specific fuel consumption (BSFC) and brake thermal efficiency are the performance indicators for engines. Not only fuel properties but also fuel injection pressure and timing, air-fuel mixture, amount of injected fuel, fuel spray pattern etc. affect engine performances. Usually engine brake power, brake torque and BSFC are tested against load or speed. Engine performance parameters for different biodiesel and their blends are discussed here.

Articles reviewed here reveal that biodiesel generally gives lower power, torque and thermal efficiency at higher fuel consumption than that of OD. Usually calorific value of biodiesel is lower than OD, thus, use of pure biodiesel or its blends as fuel reduces heat release during combustion and decreases engine performance. However, in some cases, irregular change of power [88,115] and efficiency [115] were observed. It may be because, the engines were not modified for biodiesel used and the amounts of fuel injected at different load conditions were not properly tuned.

3.1. Jatropha biodiesel

Most of the experimental results have shown that jatropha biodiesel and its blends yield higher thermal efficiency at higher fuel consumption [38,40,46,83–85]. Its blends often produce more brake power than petroleum diesel [88]. However, in some cases, lower efficiency [38,46] was also found.

Table 2 shows different experimental results of engine performance using jatropha biodiesel. In most of the cases, lower calorific value of jatropha biodiesel results in lower power-torque (2–5%) and thermal efficiency at higher BSFC (6–10%). But complete combustion characteristic of jatropha biodiesel sometimes give higher power-torque and thermal efficiency (0.2–6%).

3.2. Palm biodiesel

Palm biodiesel usually gives lower power, torque and thermal efficiency at higher fuel consumption [33,45,89]. But in some

Table 5
Different experimental engine performance results using cottonseed biodiesel compared to OD.

Engine	Test condition	Result			Reference
		Power/torque	Efficiency	BSFC	
1-Cylinder, 4S, AC, DI, CR: 1:18, D: 406 cm^3 RP: 10 HP, RS: 3600 rpm	Different speeds (1250, 1500, 1750, 2000, 2250 and 2500 rpm) and different blends (5%, 20%, 50%, 75% and 100%)	Decrease with increase of blend ratio but 5% blend gave higher torque	–	Increase with the increase of blend ratio	[24]
1-Cylinder, 4S, AC, DI, CR: 1:18, D: 395 cm^3 RP: 6.2 kW, RS: 3600 rpm	Different speeds (3100, 2800, 2500, 2200, 1900, 1600 and 1300 rpm) and 75% blend	Slightly lower	–	Slightly higher than OD	[48]
1-Cylinder, 4S, NA, DI, CR: 1:18 D: 395 cm^3 RS: 3600 rpm	Different speed and preheated biodiesel at different temperatures (30, 60, 90 and 120 °C)	90 °C preheated gave minimum average reduction (1.92%), 120 °C preheated gave maximum average reduction (7.59%)	Higher than OD and increased with the increase of preheating	–	[115]
6-Cylinder, 4S, WC, DI, TC, CR: 1:18, D: 5958 cm^3 RP: 177 kW, RS: 2600 rpm	Two different speeds (1200 and 1500 rpm), different loads (20%, 40% and 60%) and different fuel blends	–	Almost same as OD	Increased with increase of blend ratio	[49,50]
1-Cylinder, 4S, WC, DI, CR: 1:18, D: 661 cm^3	Constant speed (1500 rpm) and different loadings	–	Maximum decreased by about 2%	Increased by about 3–7%	[132]

Table 6
Different experimental engine performance results using sunflower biodiesel compared to OD.

Engine	Test condition	Result			Reference
		Power/torque	Efficiency	BSFC	
4-Cylinder, 4S, DI, WC RP:55 kW RS: 4500 rpm CR:21.5:1	Full load and variable speeds	Maximum about 10% lower	–	2–5% higher	[135]
1-Cylinder,4S CR:17.5:1 RP: 4.4 kW RS: 1500 rpm	Constant 1500 rpm speed with different loadings (20%, 40%, 60% and 80%) and different blends (20%, 40%, 60%, 80% and 100%)	–	–	Almost same as predicted	[136]
1-Cylinder, 4S, NA, AC, DI CR: 17.5:1, D: 0.661 L RP: 4.4 kW, RS: 1500 rpm	Constant 1500 rpm speed with different loads	–	2–5% increased	6–12% increased	[134]
4-Cylinder, 4S, TC, IDI, CI, WC CR: 21.5:1, D: 1753 cm^3 RP: 55 kW, RS: 4500 rpm	17.5% blend, 1500–3000 rpm speed and different loads (50%, 75% and 100%)	Slightly higher	Slightly higher	Slightly higher	[52]
6-Cylinder,4 S,TC CR: 15:1, D: 9.6 L RP:180 kW, RS: 2200 rpm	Full load, different speed and different blends (5% and 30%)	Slightly higher for 5% blend. About 2–3% lower for 30% blend	–	Almost same	[97]

cases, it gave higher thermal efficiency and lower fuel consumption than petroleum diesel [44].

Table 3 contains engine performance results extracted from different experiments at different conditions. Most of the cases use of palm biodiesel increases the fuel consumption by 7–16% and produces relatively lower power-torque (2–7%) and thermal efficiency (0.5–2%). However, in some cases thermal efficiency was almost same as OD [42,43,122,123].

3.3. Coconut biodiesel

Engine performance test using coconut biodiesel usually gives lower brake power, brake thermal efficiency at higher fuel consumption [42,43,128–130]. But some of the experimental results also gave higher thermal efficiency [128,131].

Table 4 represents different experimental results of engine performance using coconut biodiesel. It shows that, in most of the cases coconut biodiesel gives lower power at higher BSFC (2–7%) though the thermal efficiency is higher or almost the same as OD. It may be because of the lower calorific value of coconut biodiesel [52].

3.4. Cottonseed biodiesel

Cottonseed biodiesel gives poor result in engine performance test like lower power, torque and efficiency but higher fuel consumption [24,48–50]. However, sometimes under some specific conditions it gives higher efficiency [50,115].

Table 5 represents different experimental engine performance results using cottonseed biodiesel. Because of lower calorific value, most of the cases it gives lower power, torque and thermal efficiency at higher fuel consumption (3–7%). However, preheated fuel sometimes gives higher thermal efficiency because of good atomization and better combustion.

3.5. Sunflower biodiesel

Sunflower based biofuel can be considered as a good alternative fuel regarding thermal efficiency [47,52,133] but fuel consumption is increased [47,51,52,133]. However, power and torque characteristics depend on blend ratio and testing conditions [52,97].

Different experimental results at different conditions using sunflower biodiesel are represented in Table 6. Sunflower biodiesel is inferior to OD regarding engine performance for higher fuel consumption (2–12%) and lower power-torque generation (2–10%). However, presence of this biodiesel in blends sometimes increases thermal efficiency (2–5%) [134].

3.6. Soybean biodiesel

Higher fuel consumption is very common for using soybean biodiesel [54,55,58,60]. Power and torque behavior is usually inferior [54,55,104] though sometimes higher brake power [58] and efficiency [55] were found.

Table 7 represents different experimental results of engine performance test at different conditions. From the tables 5–15% blends of soybean biodiesel sometimes give higher thermal efficiency and higher power with lower fuel consumption than that of OD. However, in most of the cases, power decreases and fuel consumption increases as the biodiesel concentration increased.

Table 7
Different experimental engine performance results using soybean biodiesel compared to OD.

Engine	**Test condition**	**Result**			**Reference**
		Power/torque	Efficiency	BSFC	
4-Cylinder, 4S, NA, DI, CR: 16.8:1, D:3.14 L RS:2400 rpm	Full load, different blends (5%, 20%, 50% and 100%)	Reduction from 2.35 to 5%	Increased with increase of blend ratio	Increased with increase of blend ratio	[55]
4-Cylinder, 4S, NA, DI, D: 3.14 L RS: 2400 rpm, RP: 46 kW	Full load, different speed and different injection pressures	Lower than OD and with increase of injection pressure power decreased	–	Higher than OD and with increment of injection pressure BSFC increased	[54]
6-Cylinder, 4S, DI, TC D: 4.2 L, CR: 17.8:1 RS: 2400 rpm, RP: 46 kW	At full load, different speed and different blends (5%, 10%, 15%, 20% 25% and 30%)	Increased up to 1.15% for 10% blend and for higher blends decreased up to 4.75%	20% blend gave the maximum 4.10% increment of efficiency and then decreased with increase of blend ratio	10% blend gave maximum 1.73% reduction and then increased with increase of blend ratio	[98]
1-Cylinder, NA, 4S,WC, DI, CR: 16.5:1 D: 0.996 L RP:11.03 kW, RS:2000 rpm	At full load and different engine speeds	Almost same as OD	–	About 10% higher than OD	[104]
4-Cylinder, D: 3922 cm^3 RS: 2400 rpm, RP: 46 kW	Different load and different blends (5%, 20%, 35%, 50% and 85%)	–	–	Increased with the increase of blend ratio	[60]
1-Cylinder, NA, 4S, CR: 17:1, D: 1.84 L	Different load and different blends (20%, 50% and 100%)	–	–	15–18% higher than OD and increased with increase of blend ration	[137]
2-Cylinder, DI, CR: 18:1, D: 1272 cm^3 RS:3000 rpm	Different speed and different blends (25%, 50%, 75% and 100%)	Lower than OD and decrease with the increase of blend ratio	Higher than OD and increase with increase of blend ratio	Higher than OD and increase with increase of blend ratio	[138]
6-Cylinder, 4S, DI CR: 17.3:1 D: 2.7 L	Different percentage of EGR (38%, 43%, 49% and 54%) and different injection timing (−4 to +4 ATDC)	–	–	Increased with increase of EGR and retard of IT	[139]
4-Cylinder, DI, CR: 1:19.5 D: 1.7 L RP: 66 kW RS: 4200 rpm	Different speed (1500, 2000 and 2300 rpm), different BMEP (1, 2.6, 2, 4.2 bar) and different percentage of EGR (11–32%)	–	About 2% increased for 5% blend About 1% decreased for 20% blend	About 1.5% decreased for 5% blend About 3% increased for 20% blend	[128]

Table 8
Different experimental engine performance results using canola or rapeseed biodiesel compared to OD.

Engine	Test condition	Result			Reference
		Power/torque	Efficiency	BSFC	
4-Cylinder, 4S, NA, DI, WC, D: 3.14 L, CR:16.8:1 RS: 2400 rpm, RP: 51 kW	Full load, different speed, NA and TC	About 10% reduced for NA condition and about 16% increased for TC condition compare to OD at NA	About 1–3% increased for NA condition and about 5–6% increased for TC condition compare to OD at NA	About 6–8% increased for NA condition and about 4–6% reduced for TC condition compare to OD at NA	[57]
4-Cylinder, 4S, TC, DI, D:1.91 L, CR:18.45:1 RS: 4000 rpm, RP: 77 kW	Constant speed and different load	Almost same	–	13–15% increased	[140]
1-Cylinder, 4S, WC, DI, CR: 1:16.3, D: 1007 cm^3 RP: 11.77 kW, RS: 2200 rpm	Fixed speed (2000 rpm), different loads (0%, 25%, 50%, 75% and 100%)	–	Almost same	12–17% increased	[42]
4-Cylinder, 4S, WC, DI, NA D: 4.75 L CR:16:1 RP: 59 kW	Different speed (1400, 1600, 1800, 2000 and 2200 rpm) and different blends (5%, 10%, 20 and 35%)	–	10% blend gave the maximum and about 1% higher than OD. For 100% blend, maximum about 1–2% reduced	10% blend gave the lowest and lower than OD. For 100% blend, maximum about 10–15% increased	[100]
1-Cylinder, 4S, WC, DI, NA D:1.007 L CR:16.3 RP: 11.77 kW, RS: 2200 rpm	Constant speed (2000 rpm) and different loads (0%, 25, 50, 75 and 100%)	–	Almost same	–	[122]
1-Cylinder, 4S, NA, DI, D: 0.773 L CR:15.5:1 RP:8.6 kW RS: 2500RPM	Constant speed, constant load, different blends (20%, 50% and 100%) and different percentages of EGR (0%, 10% and 20%)	–	Lower and decreased about 1–2% with increase of blend ratio and EGR percentage	Slightly higher and increased with increase of blend ratio and EGR percentage	[59]
4-Cylinder, 4S, NA, DI, D: 3.14 L RP: 46 kW, RS: 2400 rpm	Full load, different speeds and different injection pressures	Lower than OD and with increase of injection pressure power decreased	–	Higher than OD and with increment of injection pressure BSFC increased	[54]
1-Cylinder, 4S, WC, NA, CR: 20:1, D: 450 cm^3 RS: 4500 rpm, RP: 8 kW	Constant speed (2000 rpm), different loads (40%, 60% and 80%) and 30% blend	–	–	2.3–3.5% increased	[141]
1-Cylinder, 4S, NA, DI, CR: 17.8:1, D: 857 cm^3 RS: 2400 rpm, RP: 12.5 kW	Full load and different biodiesel	2% decreased	–	26% increased	[105]

3.7. Canola or rapeseed biodiesel

Generally lower brake power and torque at higher fuel consumption is very common for canola or rapeseed based biodiesel [54,56,57,59]. However, it often provides higher thermal efficiency [53,57].

From Table 8, it is clear that use of canola or rapeseed biodiesel increase fuel consumption up to 26% and engine output power lowers up to 10%. However, turbocharging increased brake power up to 16% and change in thermal efficiency varied up to 6%.

4. Engine emission

Now-a-days, people are much more concerned about environment. Besides, the governments are introducing strict emission regulation for automobiles. For this reason; a commercial fuel has to meet the emission standards. Thus the study of engine emission has got much more importance at present. In the modern world, engine performance as well as emission is taken into consideration for the fuel selection. In this respect, biodiesel is considered as a good alternative of fossil fuel as it creates less environmental impacts [142]. This paper also illustrates the emission characteristic of different biodiesel and their blends. Usually presence of additional oxygen in biodiesel gives complete combustion of fuel and reduces CO, HC and smoke emission but increases NO_x. Sometimes irregularities were observed in case of change of emission [40]. The unmodified fuel injection system of the engine may be the reason of the irregularity. The fuel injection system, specially designed for definite biodiesel may resolve this issue.

4.1. Jatropha biodiesel

The emission characteristic for jatropha biodiesel highly depends on engine operation condition and blend ratio. Though some of the experimental results gave lower emission of CO, HC, NO_x and smoke [40,46,88,116], higher emission was also observed [38,46,83,84,88,116].

Table 9 gives an overview of emission using jatropha biodiesel. Most of the time, jatropha biodiesel and its blend reduce CO, HC and smoke emission and increase NO_x. But in some cases reduction of NO_x was observed because of the lower heating value of jatropha biodiesel.

Table 9
Different experimental engine emission results using jatropha biodiesel compared to OD.

Engine	Test condition	Emission				Reference
		CO	HC	NO_x	Smoke	
3-Cylinder, WC, CI engine, D: 3.44 L, CR:18:1 RS: 2200 rpm	Full throttle at different engine speed	Higher than ordinary diesel but reduced with increase of blend ratio	Lower than OD but increased with the increase of blend ratio	Always higher than OD	Reduced with the increase of blend ratio and engine speed	[88]
1-Cylinder, 4S, WC,DI, CI engine, CR: 1:17, D: 815 cm³ RP: 8.82 kW, RS: 2000 rpm	Constant speed (1500 rpm and 2000 rpm) at different power	Lower than OD at high loads; almost the same as OD at low load.	Lower than OD and decreased more at higher speed	Lower at low load and speed higher at high load	–	[40]
1-Cylinder, 4 S, WC, CR: 1:17.5 D: 2645.81 cm³ RP: 5.2 kW RS: 1500 rpm	Speed: 1500 rpm IA: 23° bTDC IP: 160 kg/cm². Different brake powers. Different blends (20%, 40%, 60% and 100%).	–	–	Higher than OD and increase with the increase of blending ratio	Lower than OD only for 20% blend	[84]
	Speed: 1500 rpm IP: 160 kg/cm². Different brake powers. Different IA (21°–25° bTDC) for 20% blend	–	–	21° bTDC gives the lowest	23° bTDC gives the lowest	
1-Cylinder, 4S, WC, RP: 8 bhp RS: 1500 rpm	Different brake powers for different blends (25%, 50%, 75% and 100%) at constant speed	Higher than OD but at pick load lower emission observed	Lower than OD and decreased with increase of blend ratio	Higher than OD and increased with blend ratio	Always lower than OD	[46]
1-Cylinder, AC, DI, CR: 1:18 D: 395 cm³ RP: 5.59 kW RS:3600 rpm	Different speeds (3200 rpm, 2500 rpm, 1800 rpm), different torques (5 Nm, 10 Nm and 15 Nm) and different injection timings (340, 345, 350)	Lower than OD	Lower than OD	Higher than OD	Lower than OD	[116]
1-Cylinder, AC, CR: 1:17.5 D: 947.87 cm³ RP: 7.4 kW RS: 1500 rpm	At different loads (0%, 20%, 40%, 60%, 80% and 100%) and different blends (5%, 10%, 20%, 30% and 100%)	Lower than OD and decrease with increase of blend ratio	Lower than OD and decrease with increase of blend ratio	Higher than OD and increased with the increase of blend ratio	Lower than OD and decrease with increase of blend ratio	[117]
4-Cylinder, 4S, TC, DI D: 3.3 l RP: 79 kW RS: 3200 rpm	Different loads (10%, 25%, 50% and 75%) and different blending ratios (5%, 10%, 20%, 50% and 100%) at constant speed (2000 rpm)	Higher than OD at lower load and increased with blending ratio. At higher load, emission was lower than OD and decreased with the increase of blend ratio	Lower than OD and decreased with the increase of load and blending ratio	Higher than OD and increased with the increase of load and blending ratio	Lower than OD and decreased with the increase of blending ratio	[143]
1-Cylinder, 4S, DI, WC CR: 1:18.5 D: 1.007 L RP: 19 PS, RS: 2400 rpm	At different speeds (1000–2400 rpm) and different blends (10%, 20%, 50% and 100%)	Reduced from 6.51 to 12.32% with the increase of blend ratio	Lower than OD and decreased from 14.91 to 27.53% with the increase of blend ratio	Increased from 3.29 to 10.75%	Reduced from 36.91 to 86.06% with the increase of blend ratio	[118]
4-Cylinder, 4S, TC, CR: 1:18.5, D: 2609 cm³ RP: 84.5 kW, RS: 3800 rpm	Full throttle at different speed and also optimized injection parameters to compensate power deterioration	Reduces by 10–40% but optimized injection increased emission	Always lower than OD and maximum reduction was 40% for normal injection	Normally reduced by 5–10% but optimized injection increased emission	Always lower than OD and maximum reduction was 80% for normal injection	[119]
1-Cylinder, DI, CR: 1:16.5 RP: 5 HP, RS: 1500 rpm	At different loads (25%, 50%, 75% and 100%) and different blends (20%, 40%, 50%, 60%, 800% and 100%)	Lower than OD	Lower than OD	Lower than OD	–	[120]
1-Cylinder, 4S, WC, NA, DI, CR: 1:17.5 D: 661 cm³ RP: 7 HP, RS: 1500 rpm	Full load, different blends (5%, 10%, 15%, 20%, 25% and 100%), different injection pressures (180, 200, 220 and 240 bar), different injection timings (22, 27 and 32 deg)	–	Lower than OD, Maximum at 240 bar, Minimum at 220 bar, Maximum at 22 deg, Minimum at 32 deg	Higher than OD, Maximum at 240 bar, Minimum at 180 bar, Maximum at 32 deg, Minimum at 22 deg	–	[121]

4.2. Palm biodiesel

Lower emission was expected for palm based biodiesel and many experimental results gave the expected emission characteristics [33,39,44,45,89,91,124]. But in some cases higher emission were also found [33,39,44,45,89,91,124].

Table 10 shows that in most of the cases palm biodiesel and its blends reduce emission of CO, HC and smoke in a large scale but increase NO_x up to 70%. The reduction range of CO is up to about 87%, HC is about 46% and smoke is 70%.

4.3. Coconut biodiesel

Coconut biodiesel gives very much promising emission characteristics. It usually gives lower CO, HC, smoke and NO_x emission [42,43,128–131].

Table 10
Different experimental engine emission results using palm biodiesel compared to OD.

Engine	Test condition	Emission				Reference
		CO	HC	NO_x	Smoke	
6-Cylinder, 4S, WC, NA, DI, CR: 1:15.9, D: 991 cm^3 RP: 81 kW, RS: 2600 rpm	Full load and constant speed (1500 rpm)	Decreased by 86.89%	Decreased by 14.29%	Increased by 22.13%	Decreased by 67.65%	[33]
4-Cylinder, 4S, WC, NA, IDI, CR: 1:21.47, D: 449.77 cm^3 RP: 38.8 kW, RS: 4250 rpm	Full load at different speeds and different blends (5%, 20%, 50% and 100%)	Decreased as the biodiesel percentage increased	Decreased as the biodiesel percentage increased	Increased as the biodiesel percentage increased	Decreased as the biodiesel percentage increased	[124]
4-Cylinder, 4S, NA, IDI, WC CR: 21.47:1 RP: 38.8 kW, RS: 4250 rpm	Different engine speeds at full load and different blends (10%, 30%, 40%, 60%, 80% and 100%)	Maximum about 60% decreased with increase of blend ratio	About 35% decreased with increase of blend ratio	About 70% increased as blend ratio increased 10% blend gave almost same	Maximum about 45% decreased with increase of blend ratio	[89]
6-Cylinder, 4S, DI, WC, NA CR: 15.9:1 RP: 81 kW, RP: 2600 rpm	Full load at different speeds	Maximum about 84% decreased	Maximum about 22% decreased	Maximum about 20% increased	Maximum about 70% decreased	[45]
1-Cylinder, 4S, WC, DI, NA CR: 16.5:1 RP: 3.5 kW, RS: 1500 rpm	Constant speed and different percentages of EGR (0% and 15%)	30–45% reduced	–	37–60% reduced	–	[125]
1-Cylinder, 4S, WC, DI, CR: 1:16.3, D: 1007 cm^3 RP: 11.77 kW, RS: 2200 rpm	Fixed speed (2000 rpm), different loads (0%, 25%, 50%, 75% and 100%)	About 10–15% reduced	About 35–46% reduced	Slightly decreased at full load	Maximum about 6% reduced	[43]
1-Cylinder, 4S, WC, DI, CR: 1:16.3, D: 1007 cm^3 RP: 11.77 kW, RS: 2200 rpm	Fixed speed (2000 rpm), different loads (0%, 25%, 50%, 75% and 100%)	Average about 15–25% decreased	Average about 30% decreased	Slightly reduced	About 20–34% reduced	[42]
1-Cylinder, 4S,DI, NA, AC RP: 4.6 kW, RS: 3500 rpm CR: 22:1, D: 347 cm^3	Different loads, speed and blends (50% and 100%)	Lower than OD and decreased with increase of blend ratio	26% lower	5% reduced	66.7% reduced	[126]
1-Cylinder, 4S, DI, NA, WC CR: 17.5:1, D: 662 cm^3 RP: 5.2 kW, RS: 1500 rpm	Constant speed (1500 rpm), different loads and different blends (25%, 50%, 75% and 100%)	Lower than OD and maximum about 56% decreased for 100% blend	25% blend gave about 30–40% higher blends reduced about 45%	25% blend showed slight higher 100% blend showed lower	25% blend gave about 20–30% higher. Higher blends reduced about 30–45%	[127]
1-Cylinder, 4S, WC, DI, NA D:1.007 L, CR:16.3 RP: 11.77 kW, RS: 2200 rpm	Constant speed (2000 rpm) and different loads (0%, 25, 50, 75 and 100%)	Almost same to OD	Almost same to OD, slight higher at lower loads	24% decreased at higher loads	Almost same to OD, slight lower at higher load	[122]
1-Cylinder, 4S, DI, WC CR: 23.1:1 RP: 5.88 kW, RS: 2200 rpm	Constant speed (2000 rpm) and different loads (0%, 25, 50, 75 and 100%)	Slightly higher than OD	Almost same as OD	About 15–20% lower	Almost same	[122]
1-Cylinder, 4 S, DI, WC D: 1007 cm^3, CR: 16.3:1 RP: 11.77 kW, RS:2200 rpm	Constant speed (2000 rpm) and different loads	–	About 10–20% higher	Almost same as OD	About 1–3% reduced	[123]

Table 11 represents emission characteristics of coconut biodiesel received from different experimental results. It shows that coconut biodiesel reduces emission including NO_x. The additional oxygen of coconut biodiesel leads to complete combustion and reduces CO, HC and smoke. Again lower calorific value leads to lower combustion temperature and reduce NO_x. The maximum reduction rate of CO is about 40%, HC is about 60%, smoke is about 40% and NO_x is about 10%.

4.4. Cottonseed biodiesel

The emission behavior of cottonseed based biodiesel mainly depends on engine operating conditions. Some of the experimental results showed lower emission of CO, HC, NO_x, CO_2 and smoke [24,48,94,115,132]. However, some conditions also showed higher emissions [24,49,50,94,115].

Emission characteristics from different experimental results using cottonseed biodiesel and its blends are represented in Table 12. Most of the cases, use of cottonseed biodiesel reduce CO, HC and smoke emission. Sometimes it reduces NO_x emission as lower calorific value leads to lower combustion temperature. The maximum reduction range of CO, HC, smoke and NO_x are 40%, 60%, 50% and 10%.

4.5. Sunflower biodiesel

The emissions of sunflower based biodiesel are also affected by engine operating conditions and blend ratios. Many researcher found lower emission characteristic [47,51,52,94,133] though many experimental results showed higher emission of CO and NO_x [47,51,52,94,133].

Experimental results of sunflower biodiesel and its blends are represented in Table 13. It gives an overview of emission characteristics of sunflower biodiesel. The reduction of CO, HC and smoke are approximately 65%, 60% and 25%, respectively. Again a maximum of 115% increment of NO_x emission was observed.

Table 11
Different experimental engine emission results using coconut biodiesel compared to OD.

Engine	Test condition	Emission				Reference
		CO	HC	NO_x	Smoke	
1-Cylinder, 4S, FAC, DI, CR: 1:19.9 D: 211 cm^3	Full load, constant speed (3000 rpm) and different fuel blends	Lower than OD and decreased with the increase of blend ratio	Lower than OD and decreased with the increase of blend ratio	–	Lower than OD and decreased with the increase of blend ratio	[130]
1-Cylinder, 4S, WC, DI, CR: 1:17.5 D: 661 cm^3 RP: 5.2 kW, RS: 1500 rpm	Different loads (15%, 30%, 45%, 60%, 75%, 90% and 100%) and different blends (20%, 40%, 60%, 80% and 100%)	–	Lower than OD and 20% blend gave the lowest	Almost similar to OD	Lower than OD and decreased with the increase of blend ratio	[131]
1-Cylinder, 4S, WC, DI, CR: 1:16.3 D: 1007 cm^3 RP: 11.77 kW, RS: 2200 rpm	Fixed speed (2000 rpm), different loads (0%, 25%, 50%, 75% and 100%)	30–40% lower	About 40% lower	Slightly lower	2–10% lower	[42]
1-Cylinder, 4S, AC, DI, NA, CR: 1:18.8 D: 367 cm^3 RP: 2.8 kW, RS: 3600 rpm	Full throttle at different speeds (1200–3600 rpm)	15–20% less	50–60% less	10% less	20–40% less	[129]
4-Cylinder, DI, CR: 1:19.5 D: 1.7 L RP: 66 kW, RS: 4200 rpm	Different speeds (1500, 2000 and 2300 rpm), different BMEP (1, 2.6, 2, 4.2 bar) and different percentages of EGR (11–32%)	About 9% less	About 10% less	Almost same	–	[128]
1-Cylinder, 4S, WC, DI, CR: 1:16.3 D: 1007 cm^3 RP: 11.77 kW, RS: 2200 rpm	Fixed speed (2000 rpm), different loads (0%, 25%, 50%, 75% and 100%)	30–40% lower	About 40% lower	Slightly lower	2–10% lower	[43]

Table 12
Different experimental engine emission results using cottonseed biodiesel compared to OD.

Engine	Test condition	Emission				Reference
		CO	HC	NO_x	Smoke	
1-Cylinder, 4S, AC, DI, CR: 1:18 D: 406 cm^3 RP: 10 HP, RS: 3600 rpm	Different speeds (1250, 1500, 1750, 2000, 2250 and 2500 rpm) and different blends (5%, 20%, 50%, 75% and 100%)	Decreased as the blend ratio increased, at lower speed, more change was observed at lower speed	–	Only 5% blend gave higher emission and it decreased with the increase of blend ratio	Lower blend (lower than 50%) decreased emission but increased at higher blend	[24]
1-Cylinder, 4S, AC, DI, CR: 1:18 D: 395 cm^3 RP: 6.2 kW, RS: 3600 rpm	Different speeds (3100, 2800, 2500, 2200, 1900, 1600 and 1300 rpm) and 75% blend	About 37% reduced	About 60% reduced	About 10% reduced	About 50% reduced	[48]
1-Cylinder, 4S, NA, DI, CR: 1:18 D: 395 cm^3 RS: 3600 rpm	Different speeds and preheated biodiesel at different temperatures (30, 60, 90 and 120 °C)	About 40% average reduction	–	Average increment about 25%	–	[115]
6-Cylinder, 4S, WC, DI, TC, CR: 1:18, D: 5958 cm^3 RP: 177 kW, RS: 2600 rpm	Two different speeds (1200 and 1500 rpm), different loads (20%, 40% and 60%) and different fuel blend	Lower, decreased with increase of blend ratio	Higher, increased with increase of blend ratio	Higher, increased with increase of blend ratio	–	[49,50,94]
1-Cylinder, 4S, WC, DI, CR: 1:18, D: 661 cm^3	Constant speed (1500 rpm) and different loading	Decreased by 12–16%	Decreased by 25–35%	–	Decreased by 10–15%	[132]

4.6. Soybean biodiesel

The emission characteristics of soybean biodiesel depend on engine operating condition. Though many tests showed lower emission of CO, HC, NO_x, CO_2 and smoke [54,55,58,60,104], some researchers reported higher emissions [54,55,58,60].

The emission characteristics of soybean biodiesel from Table 14 show that use of soybean biodiesel and it blends reduce emission of CO, HC and smoke by 40%, 25% and 74% respectively and increase NO_x emission up to 15%.

4.7. Canola or rapeseed biodiesel

Engine emission test results using canola or rapeseed based biodiesel most of the cases give lower emission than that of ordinary diesel [53,54,56,59,101,102,105]. However, for some specific engine operating conditions, it also showed higher emission [53,54,56,59,101,102].

Table 15 shows different experimental results regarding emission characteristic of canola or rapeseed biodiesel and blends. The average reduction of CO, HC and smoke emission using this

Table 13
Different experimental engine emission results using sunflower biodiesel compared to OD.

Engine	Test condition	Emission				Reference
		CO	HC	NO_x	Smoke	
4-Cylinder, 4S, DI, WC RP:55 kW, RS: 4500 rpm CR:21.5:1	Full load and variable speed	Slight lower than OD	Almost same as OD	–	–	[135]
1-Cylinder, 4S CR:17.5:1 RP: 4.4 kW RS: 1500 rpm	Constant 1500 rpm speed with different loadings (20%, 40%, 60% and 80%) and different blends (20%, 40%, 60%, 80% and 100%)	–	About 10–15% lower than predicted	About 20% lower than predicted	–	[136]
1-Cylinder, 4S, NA, AC, DI CR: 17.5:1, D: 0.661 L RP: 4.4 kW, RS: 1500 rpm	Constant 1500 rpm speed with different loads	Reduced about 10–65%	20–60% reduced	About 80–115% increased	–	[134]
4-Cylinder, 4S, TC, IDI, CI, WC CR: 21.5:1, D: 1753 cm^3 RP: 55 kW, RS: 4500 rpm	17.5% blend is used, 1500–3000 rpm speed range and different loads (50%, 75% and 100%)	At 50% load almost same at higher load and lower speed CO emission was higher	–	At 50% load almost same to OD. At higher load and speed 3–6% increased	–	[52]
6-Cylinder, 4S, CI, DI, WC, TC CR: 18:1, D: 5958 cm^3 RP:177 kW, RS: 2600 rpm	Different loads (20%, 40% and 60%) and different blends (10% and 20%)	–	–	About 4–10% increased with increase of blend ratio	About 10–25% decreased with increase of blend ratio	[94]
6-Cylinder, 4S, TC CR: 15:1, D: 9.6 L RP:180 kW, RS: 2200 rpm	Full load, different speeds and different blends (5% and 30%)	Lower than OD and decreased as blend ratio and speed increased	–	Slight increased with increase of blend ratio	–	[97]

Table 14
Different experimental engine emission results using soybean biodiesel compared to OD.

Engine	Test condition	Emission				Reference
		CO	HC	NO_x	Smoke	
4-Cylinder, 4S, NA, DI, CR: 16.8:1, D:3.14 L RS:2400 rpm	Full load, different blends (5%, 20%, 50% and 100%)	Decreased 3–39% with increasing of blend ratio	–	Increased 4.5–15.5% with increase of blend ratio	Decreased with increasing of blend ratio Maximum reduction 74%	[55]
4-Cylinder, 4S, NA, DI, D: 3.14 L RS: 2400 rpm, RP: 46KW	Full load, different speeds and different injection pressures	Lower than OD and with increasing speed and injection pressure it reduced	–	Higher than OD and with increasing speed and injection pressure increased	Lower than OD and with increasing speed and injection pressure it reduced	[54]
1-Cylinder, NA, 4S,WC, DI, CR: 16.5:1, D: 0.996 L RP:11.03 kW, RS:2000 rpm	At full load and different engine speed	Average 40% reduced	Average 25% reduced	Average 5% reduced	Average 50% reduced	[104]
1-Cylinder, NA, 4S, AC, DI D: 0.211 L RP: 2.0KW, RS:3600 rpm	85% of full load, different blends (20%, 50%, 75% and 100%)	Lower than OD and 50% blend gave the lowest	Lower than OD and decreases with increase of blend ratio	Lower than OD and decreases with increase of blend ratio	–	[58]
4-Cylinder, D: 3922 cm^3 RS: 2400 rpm, RP: 46 kW	Different loads and different blends (5%, 20%, 35%, 50% and 85%)	Lower than OD and reduced with increase of blend ratio	50% blend gave the lowest and lower than OD, increased for other blends	–	–	[60]
1-Cylinder, NA, 4 S, CR: 17:1 D: 1.84 L	Different loads and different blends (20%, 50% and 100%)	Lower than OD and reduced with increase of power	–	7–9% higher than OD and increase with increase of blend ration and load	Lower than OD and reduction rate increased with increase of blend ratio and load	[137]
2-Cylinder, DI, CR: 18:1, D: 1272 cm^3 RS:3000 rpm	Different speeds and different blends (25%, 50%, 75% and 100%)	–	–	–	Decreased with increasing of blend ratio	[138]
6-Cylinder, 4 S, DI CR: 17.3:1 D: 2.7 L	Different percentages of EGR (38%, 43%, 49% and 54%) and different injection timings (-4 to $+4$ ATDC)	–	–	Decreased with increase of EGR and retard of IT	–	[139]
4-Cylinder, DI, CR: 1:19.5, D: 1.7 L RP: 66 kW, RS: 4200 rpm	Different speeds (1500, 2000 and 2300 rpm), different BMEP (1, 2.6, 2, 4.2 bar) and different percentages of EGR (11–32%)	Slightly higher and increased with blend ratio	–	Slightly lower for 5% blend About 10% increased for 20% blend	–	[128]

Table 15
Different experimental engine emission results using canola or rapeseed biodiesel compared to OD.

Engine	Test condition	Emission				Reference
		CO	HC	NO_x	Smoke	
4-Cylinder, 4S, NA, DI, WC, D: 3.14 L, CR:16.8:1 RS: 2400 rpm, RP: 51 kW	Full load, different speeds, NA and TC	About 7–8% reduced for NA and about 40–45% reduced for TC compare to OD at NA	–	About 17–19% increased for NA and about 33–37% increased for TC compare to OD at NA	–	[57]
4-Cylinder, 4S, TC, DI, D:1.91 L, CR:18.45:1 RS: 4000 rpm, RP: 77 kW	Constant speed and different load	Slightly lower than OD	–	10–15% higher than OD	–	[140]
1-Cylinder, 4S, WC, DI, CR: 1:16.3, D: 1007 cm^3 RP: 11.77 kW, RS: 2200 rpm	Fixed speed (2000 rpm), different loads (0%, 25%, 50%, 75% and 100%)	10–20% increased	30–36% reduced	Maximum about 5% increased	Maximum about 25% increased	[42]
4-Cylinder, 4S, WC, DI, NA D: 4.75 L, CR:16:1 RP: 59 kW	Different speeds (1400, 1600, 1800, 2000 and 2200 rpm) and different blends (5%, 10%, 20% and 35%)	30–50% lower than OD and decreased with increase of blend ratio	10–70% reduced as blend ratio increased	10% blend gave about 1–3% lower and 100% blend gave maximum 10% higher than OD	At lower load about 3–10% lower but at higher load about 15–20% higher	[100]
1-Cylinder, 4S, WC, DI, NA D:1.007 L, CR:16.3 RP: 11.77 kW, RS: 2200rom	Constant speed (2000 rpm) and different loads (0%, 25, 50, 75 and 100%)	20–25% higher	13–20% higher	About 20% reduced at low load (below 50%) and about 10% increased at full load	About 5% reduced	[122,123]
1-Cylinder, 4S, NA, DI, D: 0.773 L, CR:15.5:1 RP:8.6 kW, RS: 2500 rpm	Constant speed, constant load, different blends (20%, 50% and 100%) and different percentages of EGR (0%, 10% and 20%)	About 15–60% lower than OD and increased with increase of EGR	About 15–50% lower than OD and increased with increase of EGR	About 18–45% higher than OD and decreased with increase of EGR	–	[59]
4-Cylinder, 4S, NA, DI, D: 3.14 L RS: 2400 rpm, RP: 46 kW	Full load, different speeds and different injection pressures	Lower than OD and with increasing speed and injection pressure it reduced	–	Higher than OD and with increasing speed and injection pressure increased	Lower than OD and with increasing speed and injection pressure, it reduced	[54]
1-Cylinder, 4S, AC, DI, D: 290 cm^3 RS: 3000 rpm, RP: 4.2 kW	German agricultural five-mode cycle with different blends (20%, 40%, 60%, 80% and 100%)	Maximum about 20% increased with increase of blend ratio	Maximum about 50% decreased with increase of blend ratio	Almost same	–	[144]
1-Cylinder, 4 S, WC, NA, CR: 20:1, D: 450 cm^3 RS: 4500 rpm, RP: 8 kW	Constant speed (2000 rpm), different loads (40%, 60% and 80%) and 30% blend	20–25% reduced	7–16% reduced	7–15% increased	–	[141]
1-Cylinder, 4S, NA, DI, CR: 17.8:1, D: 857 cm^3 RS: 2400 rpm, RP: 12.5 kW	Full load and different biodiesel	About 30–35% reduced	About 15–20% reduced	6–8% reduced	–	[105]

biodiesel or its blends are 60%, 70% and 10% respectively. Again maximum about 45% increment of NO_x emission is reported.

5. Conclusion

Diesel engines are still fuel-efficient driving power plant for automotive applications because of their superior fuel economy relative to spark ignition engines of comparable capacity. However, the increase price of diesel fuels, stringent emission regulations and foreseeable depletion of petroleum reserves force scientists to look for alternative source of energy which can meet future human demand. From this review it can be concluded that biodiesel can be a promising source of future fuel which is renewable and sustainable.

The following conclusions are drawn as a summary of the review of seven selected biodiesels:

- Individual biodiesel is inferior to OD regarding fuel properties. Coconut and palm biodiesel are better for kinetic viscosity, coconut and rapeseed biodiesel are better for density; palm and coconut biodiesel are better for cetane number; jatropha, palm and soybean biodiesel have better calorific value and jatropha and palm biodiesel are good for their high flash point. So the optimum blends of coconut–palm biodiesel or coconut–palm–jatropha biodiesel or palm–rapeseed–jatropha biodiesel can give better fuel properties than individual biodiesel.
- Biodiesel and its blends increase fuel consumption and reduce brake power and torque because of lower calorific value. But blends with low percentage of biodiesel (20% or less) sometime reduces fuel consumption and gives higher brake power because of complete combustion. However, biodiesel having higher calorific value and lower viscosity is more suitable for engine performance improvement. In this respect, jatropha biodiesel is found better than other biodiesels discussed in this paper.
- It is obvious that the use of biodiesel usually reduces CO, HC and smoke emission for the complete combustion characteristic, though it increases NO_x. But the use of coconut

biodiesel reduces emission including NO_x. Thus, with respect to engine emission, coconut biodiesel is better than any other biodiesels discussed in this paper.

- Single biodiesel cannot improve both engine performance and emission at a time. But blend of two or more biodiesels may be able to achieve this goal. In this respect, a blend of jatropha and coconut biodiesel may be a good option. The best suited biodiesels' blend and the optimum blend ratio are the scope of further research.

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